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Request for grant of a patent



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1. Your reference	JEB/MPC/4745		
2. Patent application number <i>(The Patent Office will fill in this part)</i>	9903923.2		
3. Full name, address and postcode of the or of each applicant <i>(underline all surnames)</i>	The University of Bath, Claverton Down, Bath. BA2 7AY		
Patents ADP number <i>(if you know it)</i>			
If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom 7607351001		
4. Title of the invention	Improvements in or relating to photonic crystal fibres		
5. Name of your agent <i>(if you have one)</i>	Abel & Imray		
"Address for service" in the United Kingdom to which all correspondence should be sent <i>(including the postcode)</i>	20 Red Lion Street London WC1R 4PQ		
Patents ADP number <i>(if you know it)</i>	174001		
6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and <i>(if you know it)</i> the or each application number	Country	Priority application number <i>(if you know it)</i>	Date of filing <i>(day/month/year)</i>
7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application	Date of filing <i>(day/month/year)</i>	
8. Is a statement of inventorship and of right to grant of a patent required in support of this request? <i>(Answer 'Yes' if:</i> a) <i>any applicant named in part 3 is not an</i> <i>inventor, or</i> b) <i>there is an inventor who is not named as an</i> <i>applicant, or</i> c) <i>any named applicant is a corporate body.</i>	Yes		

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Description 15

Claim(s) 6

Abstract 0

Drawing(s) 10 X 10

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Priority documents

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Statement of inventorship and right to grant of a patent (*Patents Form 7/77*)

Request for preliminary examination and search (*Patents Form 9/77*) 1

Request for substantive examination (*Patents Form 10/77*)

Any other documents
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11.

I/We request the grant of a patent on the basis of this application.

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Date

Abel & Imray 19th February 1999

ABEL & IMRAY

12. Name and daytime telephone number of person to contact in the United Kingdom Mr. J. E. Bardo 01225 469914

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Improvements in or relating to photonic crystal fibres

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Improvements in or relating to photonic crystal fibres

This invention relates to photonic crystal fibres and to a method of producing photonic crystal fibres.

5 A photonic crystal fibre is a special form of optical fibre. Optical fibres are used in many fields including telecommunications, laser machining and welding, laser beam and power delivery, fibre lasers, sensors and medical diagnostics and surgery. They are typically made entirely
10 from solid transparent materials such as glass and each fibre typically has the same cross-sectional structure along its length. The transparent material in one part (usually the middle) of the cross-section has a higher refractive index than the rest and forms an optical core within which
15 light is guided by total internal reflection. We refer to such a fibre as a standard fibre.

Single-mode optical fibres are preferred for many applications because of their superior wave-guiding properties. However, even so-called single-mode optical
20 fibres do not generally offer adequate control over the polarisation of propagating light. A single-mode fibre is so called because it supports only one transverse spatial mode at a frequency of interest, but that spatial mode exists in two polarisation states; that is two degenerate
25 modes that are polarised in orthogonal directions. In real fibres, imperfections will break the degeneracy of those modes and modal birefringence will occur; that is, the mode propagation constant β will be slightly different for each of the orthogonal modes. Because the modal birefringence
30 results from random imperfections, the propagation constants will vary randomly along the fibre. In general, light introduced into the fibre will propagate in both modes and will be coupled from one to the other by small bends and

twists in the fibre. Linearly polarised light will be scrambled into an arbitrary polarisation state as it propagates along the fibre.

In order to maintain the polarisation of a mode in a standard fibre, birefringence can be deliberately introduced into the fibre (so that the effective indices of the two polarisation modes are different) in order to render insignificant the effects of small imperfections. If light is linearly polarised in a direction parallel to one of the optic axes of the fibre then the light will maintain its polarisation. If it is linearly polarised at some other angle, the polarisation will change, as the light propagates down the fibre, from linear to elliptical to linear (not parallel to the starting polarisation) to elliptical and back to linear again, with a period known as the beat length, L_B , where $L_B = \frac{2\pi}{|\beta_x - \beta_y|}$ and β_x and β_y are the

propagation constants of the orthogonal modes. That variation is a consequence of a phase difference between two orthogonal components of the mode, which results from the difference in their propagation constants. The shorter the beat length, the more resilient is the fibre to polarisation-scrambling effects. Typically, conventional polarisation-preserving fibre has a beat length of the order of a millimetre. The strength of birefringence can also be

represented by the parameter $B = \frac{|\beta_x - \beta_y|}{k_0} = |n_x - n_y|$, where

$k_0 = \frac{2\pi}{\lambda}$ (where λ is the wavelength) and n_x and n_y are the refractive indices seen by the orthogonal modes.

In the last few years a non-standard type of optical fibre has been demonstrated, called the photonic-crystal fibre (PCF). Typically, this is made from a single solid,

and substantially transparent, material within which is embedded a periodic array of air holes, running parallel to the fibre axis and extending the full length of the fibre. A defect in the form of a single missing air hole within the 5 regular array forms a region of raised refractive index within which light is guided, in a manner analogous to total-internal-reflection guiding in standard fibres. Another mechanism for guiding light is based on photonic-band-gap effects rather than total internal reflection. 10 Photonic-band-gap guidance can be obtained by suitable design of the array of air holes. Light with particular propagation constants can be confined to the core and will propagate therein.

Photonic-crystal fibre can be fabricated by stacking 15 glass canes, some of which are capillaries on a macroscopic scale, into the required shape, and then holding them in place while fusing them together and drawing them down into a fibre. PCF has unusual properties such as the ability to guide light in a single-mode over a very broad range of 20 wavelengths, and to guide light having a relatively large mode area which remains single-mode.

Birefringence can be produced by several mechanisms. It can be caused by the anisotropic nature of the polarisability of a material; i.e. by anisotropy at an 25 atomic level. It can be caused by the arrangement of elements of a material structure at a scale larger than atomic; that phenomenon is known as form birefringence. It can also be caused by mechanical stress; that phenomenon is known as stress birefringence or the photo-elastic effect. 30 In standard fibres, form birefringence is achieved by changing the shape of the fibre cross-section; for example, by making the core or cladding elliptical. Birefringence in a weakly-guiding fibre is generally rather weak ($B \cdot 10^{-6}$).

Stress birefringence can be induced by inserting rods of borosilicate glass on opposite sides of the fibre core in the fibre pre-form. Variation in the location and shape of the borosilicate rods can induce different levels of birefringence. Stress-induced birefringence permits $B \cdot 10^{-4}$.

The methods used to produce birefringence in standard fibres, and thus to produce standard polarisation-preserving fibres, are, in general, not directly suitable for use in photonic-crystal fibre.

An object of the invention is to provide a photonic crystal fibre which is birefringent so that the fibre can be used as a polarisation-preserving fibre. Another object of the invention is to provide a method of producing such a fibre.

According to the invention there is provided a photonic crystal fibre comprising a bulk material having an arrangement of longitudinal holes and a guiding core, wherein the fibre has at most-two-fold rotational symmetry about a longitudinal axis (that is any longitudinal axis) and as a result of that lack of symmetry, the fibre is birefringent.

The arrangement of holes may be substantially periodic except for the presence of the core.

Advantageously, the birefringence is such that light with a wavelength of 1.5 microns propagating in the fibre has a beat length of less than 1 cm. More advantageously, the birefringence is such that light with a wavelength of 1.5 microns propagating in the fibre has a beat length of less than 5 mm. More advantageously, the birefringence is such that light with a wavelength of 1.5 microns propagating in the fibre has a beat length of less than 1 mm and preferably less than 0.5 mm; such short beat lengths are not generally obtainable in standard fibres.

It will be understood that in a real fibre there will inevitably be minor anomalies in the structure that mean that no fibre has absolute symmetry of any kind; in conventional photonic crystal fibres, however, it is readily apparent that the real fibre does have a considerable amount of rotational symmetry (most commonly six-fold rotational symmetry) and that symmetry is sufficiently strong to make the behaviour of the fibre similar to that of a theoretical fibre having absolute symmetry. In a similar way, where reference is made to a fibre having at-most-two-fold rotational symmetry, it should be understood that not only does the fibre not strictly have any higher symmetry but, furthermore, it does not behave as would a fibre which had a significant amount of higher symmetry.

In its broadest aspect, the invention is concerned with a lack of higher rotational symmetry in any aspect of the fibre. Most typically, the lack of symmetry may arise in some feature of the internal microstructure of the fibre and, commonly, of the arrangement of holes, whilst the overall cross-sectional shape of the fibre may be circular and thus have circular symmetry; it is within the scope of the invention for the arrangement of holes to have more-than-two-fold rotational symmetry but for the fibre to lack more-than-two-fold rotational symmetry in some other sense and examples of such arrangements are given below.

Preferably, the fibre has two-fold rotational symmetry.

Preferably, the rotational symmetry is about an axis passing through the core.

If a fibre has greater than two-fold rotational symmetry then linearly polarised light would have the same propagation constant β when polarised parallel to two or more (not necessarily orthogonal) axes. As is the case in a

real fibre with circular symmetry, imperfections in the fibre will result in power transfer between modes polarised parallel to each of those axes. Consequently, light which is initially linearly polarised will excite additional modes
5 and quickly become randomly polarised.

The core may include a hole. The hole may be filled with material other than air. Alternatively, the core may not include a hole.

The arrangement of holes may have at-most-two-fold
10 rotational symmetry parallel to the longitudinal axis of the fibre. Alternatively, the arrangement of holes may have higher-than-two-fold rotational symmetry about an axis parallel to the longitudinal axis of the fibre. The rotational symmetry may be about an axis passing through the
15 core.

The lack of higher rotational symmetry may at least partly result from a variation, across the cross-section of the fibre, in one or more of the following: the microstructure of the core, the diameter of the holes, the
20 bulk material, the material contained in the holes or the shape of the holes. The shape variation may be due to deformation resulting from stresses in the fibre as it is drawn. The lack of higher rotational symmetry may result from a variation across the cross-section of the fibre, in
25 one of the following in combination with one or more of the following or with a variation in another parameter: the microstructure of the core, the diameter of the holes, the bulk material, the material contained in the holes, the shape of the holes.

30 The birefringent fibre may have form birefringence and/or stress birefringence. Although form birefringence in standard fibres is not sufficient to give the required short beat length, the potentially much larger refractive index

contrast in photonic crystal fibres can result in strong form birefringence. A new effect, not possible with standard fibres, is found when the pattern of stresses within the fibre during the draw process distorts certain of 5 the air holes surrounding the fibre core along one axis, giving additional birefringence.

Also according to the invention, there is provided a method of producing a birefringent photonic crystal fibre, the method comprising the following steps:

- 10 (a) forming a stack of canes, at least some of which are capillaries, the stack including canes arranged to form a core region in the fibre and canes arranged to form a cladding region in the fibre; and
- 15 (b) drawing the stack of canes into a birefringent fibre, which has at-most-two-fold rotational symmetry about a longitudinal axis.

Birefringence is thus introduced by modification of the method used to fabricate the photonic crystal fibre preform.
20 The modification of the fabrication procedure may consist of the reduction in material symmetry to at-most-two-fold symmetric features in the periodic stack of canes which comprise the preform. Such structures will, in general, change both the shape of the guided mode and the pattern of 25 stresses within the photonic crystal structure.

One way in which birefringence can be introduced is by including in the preform different capillaries at two-fold symmetric pairs of lattice sites. Those inclusions might be placed near to the core so as to alter the shape of the 30 guided mode ("form birefringence") or they might be placed some way from the core but be made of a material with different properties, thus altering the pattern of stresses within the fibre core ("stress birefringence"). The preform

may be structured so as to introduce birefringence by forming substantial parts of the fibre preform from a different type of capillary, which again introduces both stress and form birefringence. The basic periodic lattice 5 which forms the waveguide cladding could be a simple close-packed array of capillaries with nominally identical external diameters or it could be an array of capillaries with generally different morphological characteristics, and forming different periodic structures. A square lattice may 10 be formed from capillaries and rods with different diameters. Square and rectangular lattices can be used to build up naturally birefringent crystal structures for the cladding, simplifying the design of polarisation-preserving photonic crystal fibre.

15 The lack of higher rotational symmetry may at least partly result from variations, across the cross-section of the stack, in the internal diameters of the capillaries, in the material of which the canes are made, in the material with which the capillaries are filled and/or in the external 20 diameter of the canes.

Canes may be provided at the vertices of a cladding lattice which has at-most-two-fold rotational symmetry about the centre of the canes arranged to form the core. Capillaries of selected internal diameters may be provided 25 at the vertices of a cladding lattice which has at-most-two-fold rotational symmetry about the centre of the canes arranged to form the core, the selected diameters of the capillaries at the vertices of the cladding lattice being different from the diameters of the capillaries at other 30 sites.

A substantial number of cladding canes, near to the canes arranged to form the core, may be different.

Birefringence may at least partly result from stresses formed within the fibre as it is drawn. The stress may be introduced by the inclusion, at sites having at-most-two-fold rotational symmetry, of a cane made from a different material from that of which at least some of the other canes in the lattice are made. The stress may be introduced by the inclusion, at sites having at-most-two-fold rotational symmetry, of capillaries having a different capillary wall thickness from that of at least some of the other capillaries.

The stresses may result in the deformation of holes surrounding the core of the drawn fibre and that deformation may result in birefringence.

The stresses may result in stresses in the core of the drawn fibre and those stresses may result in birefringence.

The lack of higher rotational symmetry may at least partly result from pressurisation and/or evacuation of at least one of the capillaries during the drawing of the stack.

In any of the above-described methods, the rotational symmetry of the stack of canes is preferably two-fold rotational symmetry.

By way of example only, an embodiment of the invention will now be described, with reference to the accompanying drawings, of which:

Fig. 1 is a schematic diagram of an example of a standard fibre.

Fig. 2 is a schematic diagram of a conventional photonic-crystal fibre having a high-index core defect.

Fig. 3 is a schematic diagram of a conventional photonic-crystal fibre (a photonic-band-gap fibre) having a low-index core defect.

Fig. 4 is a schematic diagram of a photonic-crystal-fibre preform which has been partially drawn into a fibre.

Fig. 5 is a schematic cross-sectional diagram of a first polarisation-preserving photonic-crystal fibre
5 according to the invention, in which the cladding holes form a rectangular lattice.

Fig. 6 is a schematic cross-sectional diagram of a second polarisation-preserving photonic-crystal fibre according to the invention, in which the pattern of cladding holes near to the core has two-fold symmetry.
10

Fig. 7 is a schematic cross-sectional diagram of a third polarisation-preserving photonic-crystal fibre according to the invention, in which the pattern of cladding holes far from the core has two-fold symmetry.

15 Fig. 8 is a schematic cross-sectional diagram of a fourth polarisation-preserving photonic-crystal fibre according to the invention, in which the pattern of dielectric inclusions in the cores of the lattice has two-fold symmetry.

20 Fig. 9 is a schematic cross-sectional diagram of an arrangement of canes for forming a photonic crystal fibre having a square lattice.

25 Fig. 10 is a schematic cross-sectional diagram of a portion of a photonic crystal fibre having a square lattice of holes each having one of two different diameters.

Fig. 11 shows a photonic crystal fibre having a square lattice.

Fig. 12 shows canes forming part of a stack for forming a photonic crystal fibre.

30 Fig. 13 shows a photonic crystal fibre formed from a stack such as that shown in Fig. 12.

Standard fibres, such as the example shown in Fig. 1, in their simplest form comprise essentially a cylindrical

core 10 and concentric cylindrical cladding 20. Typically, both the core and the cladding will be made of the same material, usually silica, but each is doped with other materials in order to raise the refractive index of the core 5 10 and lower the refractive index of the cladding 20. Light, of appropriate wavelengths, is confined to the core 10, and guided therein, by total internal reflection at the core-cladding boundary 15.

A typical photonic crystal fibre, shown in Fig. 2, 10 comprises a cylinder of transparent bulk material 30 (e.g. silica) with a lattice of cylindrical holes 40, which run along its length. The holes are arranged at the vertices and centres of regular hexagons, which have six-fold rotational symmetry. The holes have a regular period, broken 15 by the omission of one hole near the centre of the fibre. The region 50 of the fibre surrounding the site of the missing hole has the refractive index of the bulk material 30. The refractive index of the remainder of the fibre is attributable to the refractive index of both the bulk 20 material 30 and the air in the holes 40. The refractive index of air is lower than that of, for example, silica and, consequently, the 'effective refractive index' of the material with the holes is lower than that of the region 50 surrounding the missing hole. The fibre can therefore 25 confine light approximately to the region 50, in a manner analogous to waveguiding by total internal reflection in standard fibres. The region 50 is therefore referred to as the 'core' of the photonic crystal fibre.

In another form of photonic crystal fibre, photonic 30 band gap guidance acts to confine light to the fibre 'core'. In the example of such a fibre shown in Fig. 3, there is a matrix of holes 70 in bulk material 30. The holes are arranged at the vertices (but not the centres, cf. Fig. 2)

of regular hexagons, which have six-fold rotational symmetry. The regularity of the matrix is again broken by a defect, but it is, in the illustrated example, an additional hole 60 at the centre of one of the lattice hexagons, that 5 hexagon being near the centre of the fibre. The area surrounding the additional hole 60 can again be referred to as the core of the fibre. Disregarding (for the moment) hole 60, the periodicity of holes in the fibre results in there being a band-gap in the propagation constants of light 10 which can propagate in the fibre. The addition of hole 60 effectively creates a region with a different periodicity, and that region can support propagation constants different from those supported in the rest of the fibre. If some of the propagation constants supported in the region of hole 60 15 fall within the band-gap of propagation constants forbidden in the rest of the fibre then light with those propagation constants will be confined to the core and propagate therein. Note that because the hole 60 is a low-index defect (it results in air being where bulk material would 20 otherwise be), total internal reflection effects are not responsible for that waveguiding in the illustrated example.

Photonic crystal fibres can be manufactured by a process, one stage of which is shown in Fig. 4. In the first stages of that process (not shown), a cylinder of bulk 25 material (e.g. silica), is milled so that it has a hexagonal cross-section, and a hole is drilled along its centre. The rod is then drawn into a cane using a fibre drawing tower. The cane is cut into lengths and the resulting, short canes 30 80 are stacked to form an array of canes, as shown in Fig. 4. The cane 100 at the centre of the illustrated array is not a capillary; i.e., it has no hole; the illustrated array will form an effective-index guidance type of fibre. The

array of canes 80 is fused together and then drawn into the final photonic crystal fibre 110.

The fibre shown in Fig. 5 has a lattice 120 of holes, which are arranged at the vertices of rectangles, which are 5 not squares. The periodicity of the lattice is broken by the omission of a hole in the region 125 near the centre of the fibre cross-section. The centre-to-centre spacing (pitch) of the holes is different parallel to axis x (pitch Λ_x) from the pitch (Λ_y) parallel to axis y. The fibre shown 10 in Fig. 5 could be manufactured using a cane which is milled to have a rectangular cross-section. The lattice of Fig. 5 has two-fold rotational symmetry and will therefore be birefringent.

Figs. 6 and 7 show photonic crystal fibres which are 15 effective-index-guidance fibres having a hexagonal lattice similar to that of the fibre of Fig. 2. Such lattices are not intrinsically birefringent. However, in the lattices of Fig. 6 and 7, holes 140 are of a larger diameter than holes 130. That anisotropy in the lattice creates a two-fold 20 rotationally symmetric pattern of holes about the region 135 where a hole is missing from the lattice.

The pattern of large holes in Fig. 6 has an effect analogous to that of form birefringence in a standard fibre. The variation of hole diameter near to the 'core' directly 25 creates a variation in the effective index seen by a guided mode.

The pattern of large holes in Fig. 7 produces stresses in the core which cause birefringence in the same way that birefringence is caused in standard fibres. A new effect, 30 not possible with standard fibres, is that the pattern of stresses within the fibre can, during the draw process, distort some of the air holes surrounding the fibre core along one axis, giving additional birefringence.

Another alternative, illustrated in Fig. 8, is for some of the holes to be filled with material other than air (so that they have a different dielectric constant). Again, the six-fold rotational symmetry of the lattice is reduced to a
5 two-fold rotational symmetry.

The stack of canes shown in Fig. 9 are of three types: large diameter canes 160 which are capillaries, small diameter solid canes 170 and a large diameter solid cane 180. The canes are arranged so that the large diameter
10 canes 160 form a square lattice, which is broken by a defect at a central site, the defect being the large diameter solid cane 180. Interstitial gaps, resulting from the non-tesselating nature of the circular cross-sections of canes 160, are filled by small diameter canes 170.

15 A photonic crystal fibre having two-fold symmetry is shown in Fig. 10. The fibre has a lattice structure which can be constructed from a stack of canes arranged in a manner similar to the stack of Fig. 9. Solid cane 180 results in a defect similar to defect 210. In this case,
20 however, alternate rows of holes (190, 200) have large and small diameters respectively. Such an effect could be achieved with the lattice of Fig. 9 by providing alternate rows of canes 160 with large and small internal diameters (but with constant external diameters).

25 The fibre of Fig. 11 can be seen to have approximately a square lattice such as might be produced from the stack of Fig. 9.

Fig. 12 shows a stack of canes 220 which are capillaries. The canes are arranged on an hexagonal
30 lattice, with the periodicity of the structure broken by a solid cane 240. It will be noted that a row of canes about half-way up the photograph are capillaries with thicker walls 250 than the walls 230 of other capillaries. When a

fibre is drawn from the stack of canes, such an arrangement will result in a fibre, such as that shown in Fig. 13, having a row of holes 260 having a smaller diameter than other holes in the fibre.

- 5 Many other patterns of capillaries and canes, varying in various parameters, could be envisaged that would fall within the scope of the invention.

CLAIMS

1. A photonic crystal fibre comprising a bulk material having an arrangement of longitudinal holes and a guiding core, wherein the fibre has at-most-two-fold rotational symmetry about a longitudinal axis and as a result of that lack of symmetry, the fibre is birefringent.
- 5 2. A photonic crystal fibre as claimed in claim 1, in which the arrangement of holes is substantially periodic except for the presence of the core.
- 10 3. A photonic crystal fibre as claimed in claim 1 or claim 2, in which the birefringence is such that light with a wavelength of 1.5 microns propagating in the fibre has a beat length of less than 5 mm.
- 15 4. A photonic crystal fibre as claimed in any preceding claim, in which the fibre has two-fold rotational symmetry.
- 5 5. A photonic crystal fibre as claimed in any preceding claim, in which the rotational symmetry is about an axis passing through the core.
- 20 6. A photonic crystal fibre as claimed in any of claims 1 to 5, in which the core includes a hole.
7. A photonic crystal fibre as claimed in claim 6, in which the hole is filled with material other than air.
- 25 8. A photonic crystal fibre as claimed in any of claims 1 to 5, in which the core does not include a hole.
- 30 9. A photonic crystal fibre as claimed in any preceding claim, in which the arrangement of holes has at-most-two-fold rotational symmetry about an

- axis parallel to the longitudinal axis of the fibre.
10. A photonic crystal fibre as claimed in any of claims 1 to 8, in which the arrangement of holes has higher-than-two-fold rotational symmetry about an axis parallel to the longitudinal axis of the fibre.
11. A photonic crystal fibre as claimed in any preceding claim, in which the lack of higher rotational symmetry at least partly results from a variation, across the cross-section of the fibre, in the microstructure of the core.
12. A photonic crystal fibre as claimed in any preceding claim, in which the lack of higher rotational symmetry at least partly results from a variation, across the cross-section of the fibre, in the diameter of the holes.
13. A photonic crystal fibre as claimed in any preceding claim, in which the lack of higher rotational symmetry at least partly results from a variation, across the cross-section of the fibre, in the bulk material.
14. A photonic crystal fibre as claimed in any preceding claim, in which the lack of higher rotational symmetry at least partly results from a variation, across the cross-section of the fibre, in the material contained in the holes.
15. A photonic crystal fibre as claimed in any preceding claim, in which the lack of higher rotational symmetry at least partly results from a variation, across the cross-section of the fibre, in the shape of the holes.

16. A photonic crystal fibre as claimed in claim 15, in which the shape variation is due to deformation resulting from stresses in the fibre as it is drawn.
- 5 17. A photonic crystal fibre as claimed in any preceding claim, in which the lack of higher rotational symmetry results from a variation across the cross-section of the fibre, in one of the following in combination with one or more of the following or with a variation in another parameter: the microstructure of the core, the diameter of the holes, the bulk material, the material contained in the holes, the shape of the holes.
- 10 18. A photonic crystal fibre as claimed in any preceding claim, in which the birefringent fibre has form birefringence.
- 15 19. A photonic crystal fibre as claimed in any preceding claim, in which the birefringent fibre has stress birefringence.
- 20 20. A method of producing a birefringent photonic crystal fibre, the method comprising the following steps:
 - (a) forming a stack of canes, at least some of which are capillaries, the stack including canes arranged to form a core region in the fibre and canes arranged to form a cladding region in the fibre; and
 - (b) drawing the stack of canes into a birefringent fibre which has at-most-two-fold rotational symmetry about a longitudinal axis.
- 25
- 30

21. A method as claimed in claim 20, in which the stack of canes is arranged to have at-most-two-fold rotational symmetry about a longitudinal axis of the stack.
- 5 22. A method as claimed in claim 20 or 21, in which the lack of higher rotational symmetry at least partly results from variations, across the cross-section of the stack, in the internal diameters of the capillaries.
- 10 23. A method as claimed in any of claims 20 to 22, in which the lack of higher rotational symmetry at least partly results from variations, across the cross-section of the stack, in the material of which the canes are made.
- 15 24. A method as claimed in any of claims 20 to 23, in which the lack of higher rotational symmetry at least partly results from variations, across the cross-section of the stack, in the material with which the capillaries are filled.
- 20 25. A method as claimed in any of claims 20 to 24, in which the lack of higher rotational symmetry at least partly results from variations, across the cross-section of the stack, in the external diameter of the canes.
- 25 26. A method as claimed in any of claims 20 to 25, in which canes are provided at the vertices of a cladding lattice which has at-most-two-fold rotational symmetry about the centre of the canes arranged to form the core.
- 30 27. A method as claimed in any of claims 20 to 25, in which capillaries of selected internal diameters are provided at the vertices of a cladding lattice which has at-most-two-fold rotational symmetry

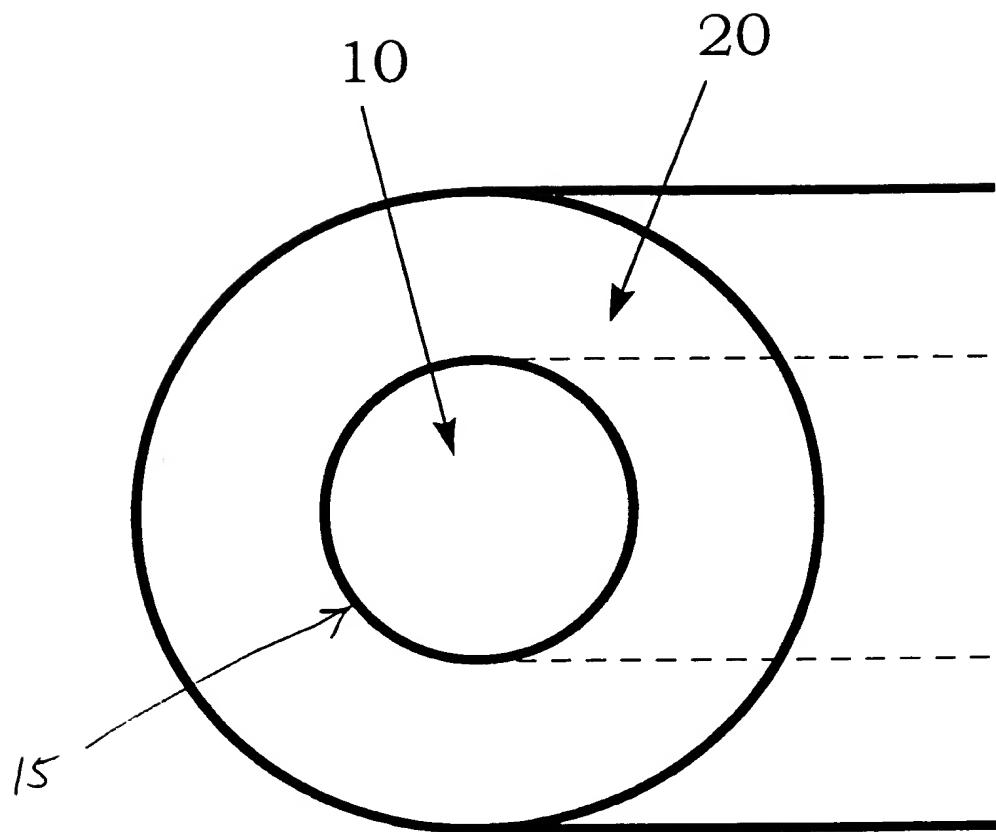
- about the centre of the canes arranged form the core, the selected internal diameters of the capillaries at the vertices of the cladding lattice being different from the internal diameters of the capillaries at other sites.
- 5 28. A method as claimed in any of claims 20 to 27, in which a substantial number of cladding canes, near to the canes arranged to form the core, are different from a substantial number of cladding canes, far from the canes arranged to form the core.
- 10 29. A method as claimed in any of claims 20 to 28, in which the birefringence results at least partly from stresses formed within the fibre as it is drawn.
- 15 30. A method as claimed in claim 29, in which the stress is introduced by the inclusion, at sites having at-most-two-fold rotational symmetry, of a cane made from a different material from that of which at least some of the other canes in the lattice are made.
- 20 31. A method as claimed in claim 29, in which the stress is introduced by the inclusion, at sites having at-most-two-fold rotational symmetry, of capillaries having a different capillary wall thickness from that of at least some of the other capillaries.
- 25 32. A method as claimed in any of claims 29 to 31 in which the stresses result in the deformation of holes surrounding the core of the drawn fibre and that deformation results in birefringence.
- 30 33. A method as claimed in any of claims 29 to 31 in which the stresses result in stresses in the core

of the drawn fibre, and those stresses result in birefringence.

34. A method as claimed in any of claims 20 to 33, in which the lack of rotational symmetry at least partly results from pressurisation of at least one of the capillaries during the drawing of the stack.
- 5 35. A method as claimed in any of claims 20 to 34, in which the lack of rotational symmetry at least partly results from evacuation of at least one of the capillaries during the drawing of the stack.
- 10 36. A method as claimed in any of claims 20 to 35, in which the rotational symmetry of the stack of canes is two-fold rotational symmetry.

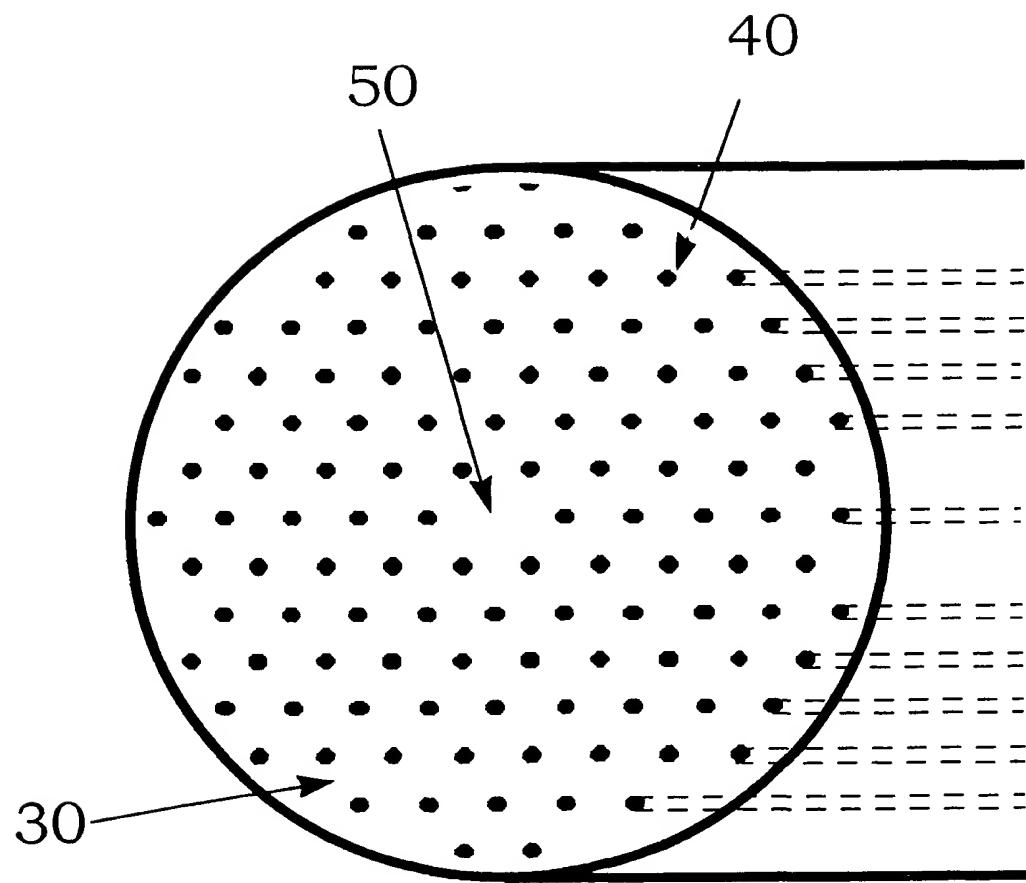
1/10

Fig. 1



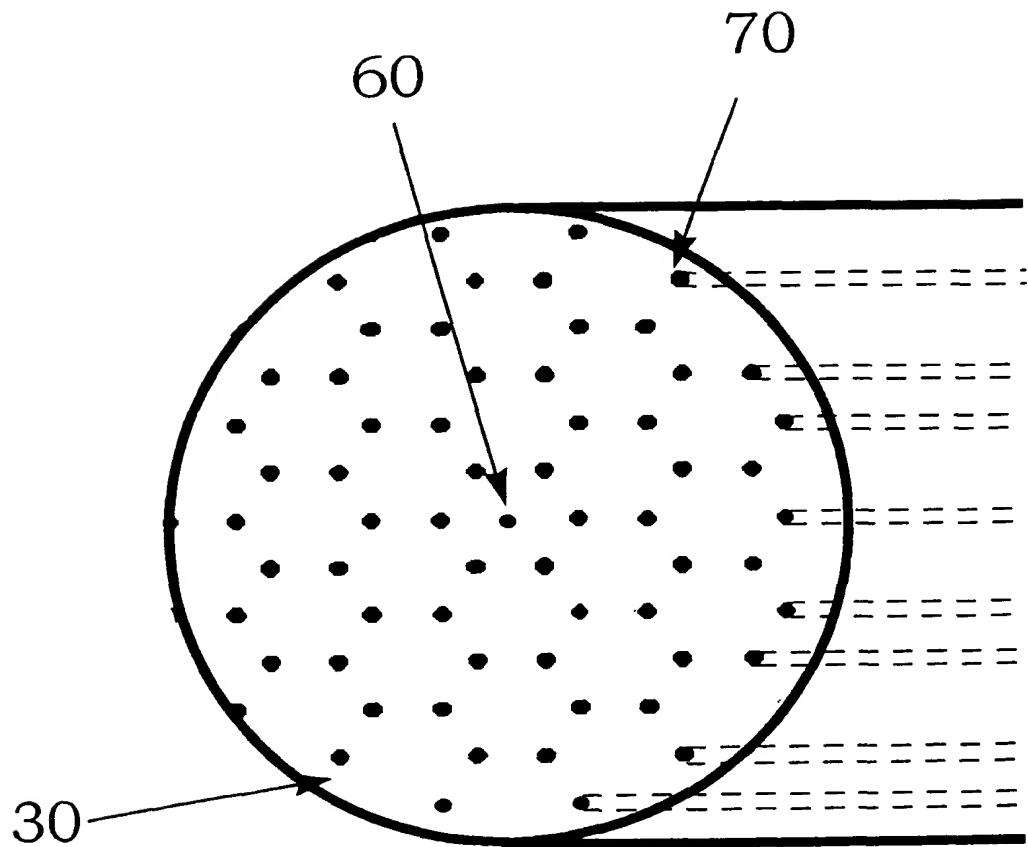
2/10

Fig. 2



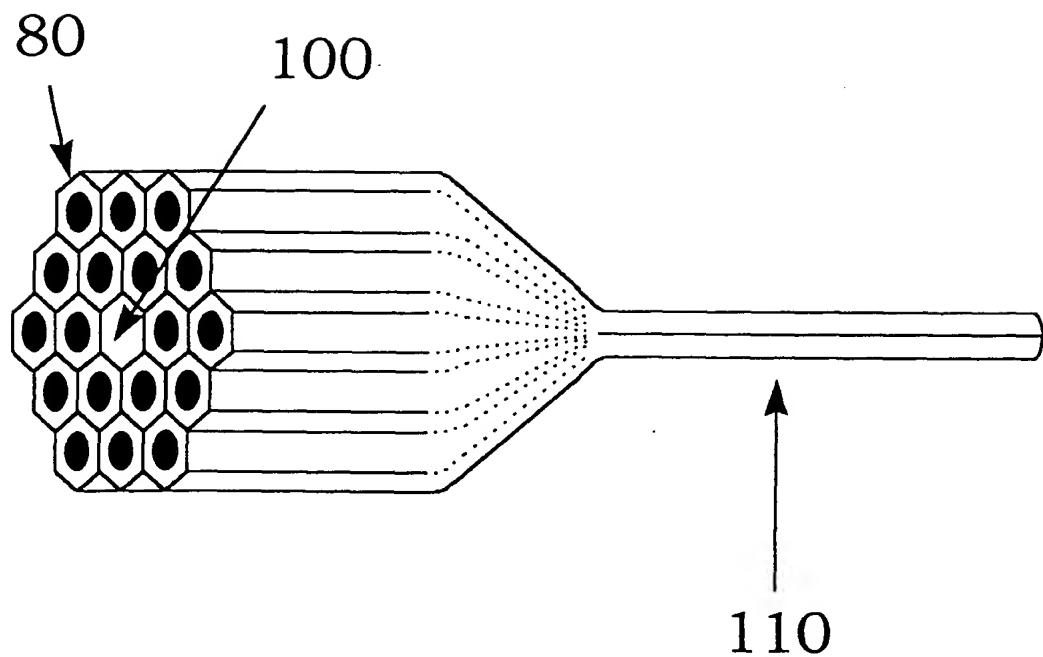
3/10

Fig. 3



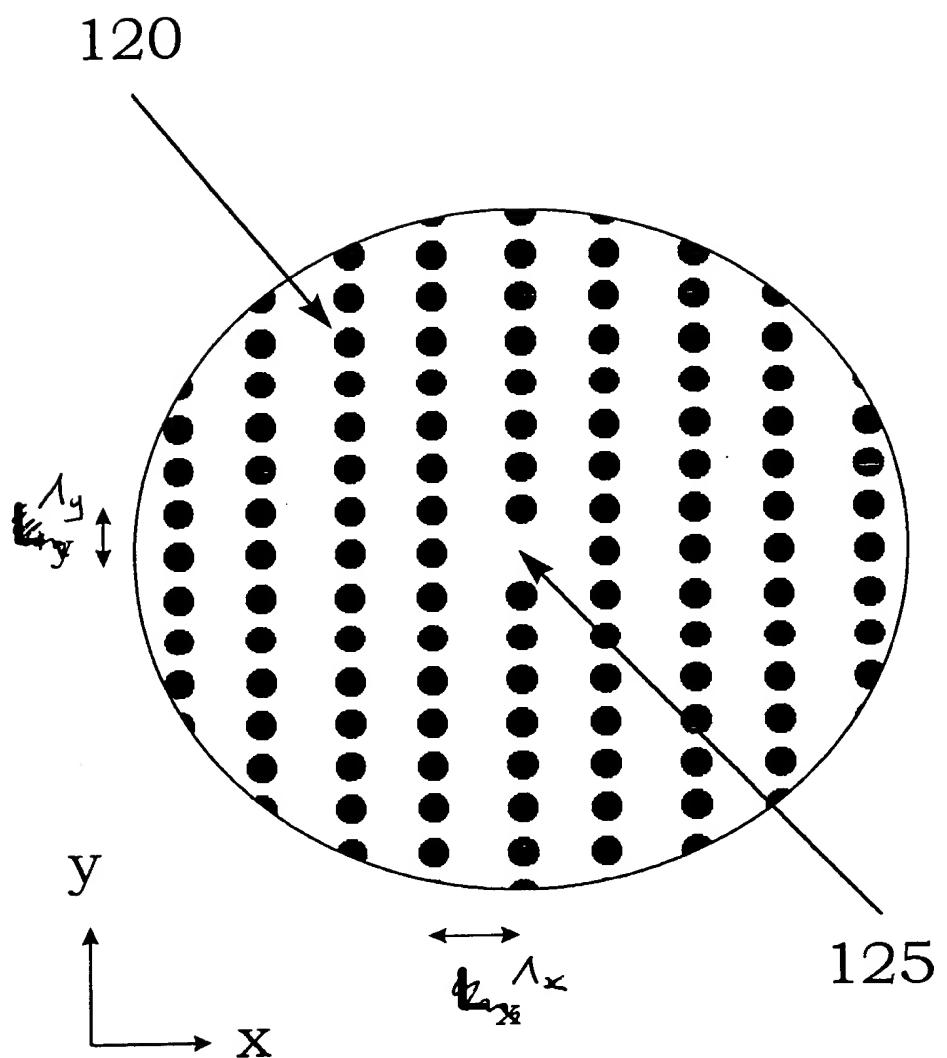
4/10

Fig. 4



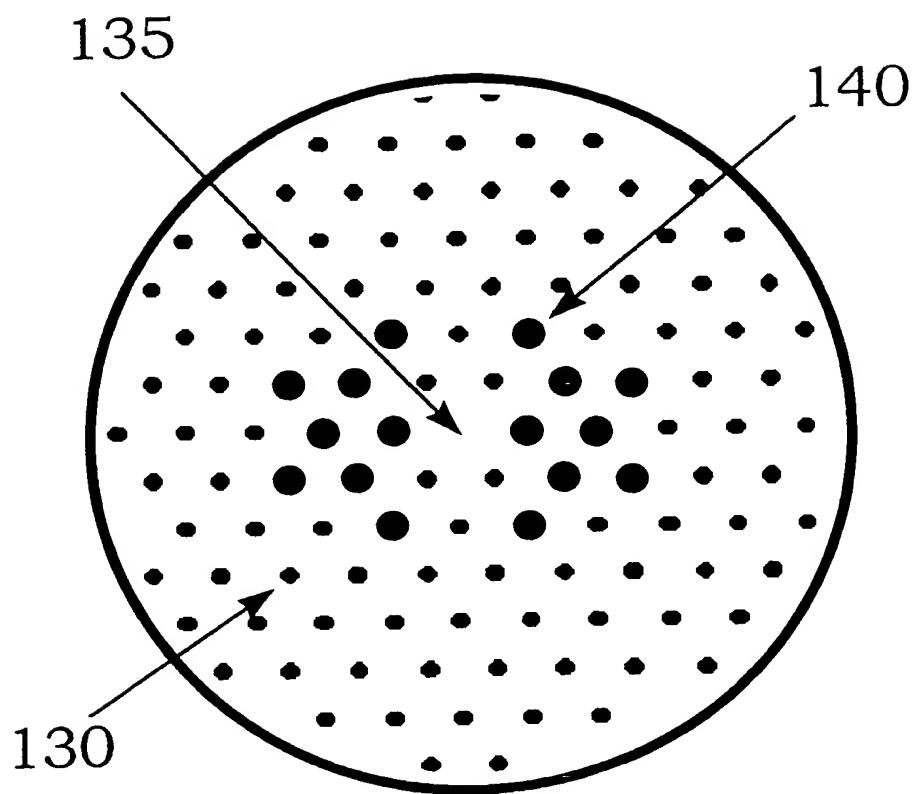
5/10

Fig. 5



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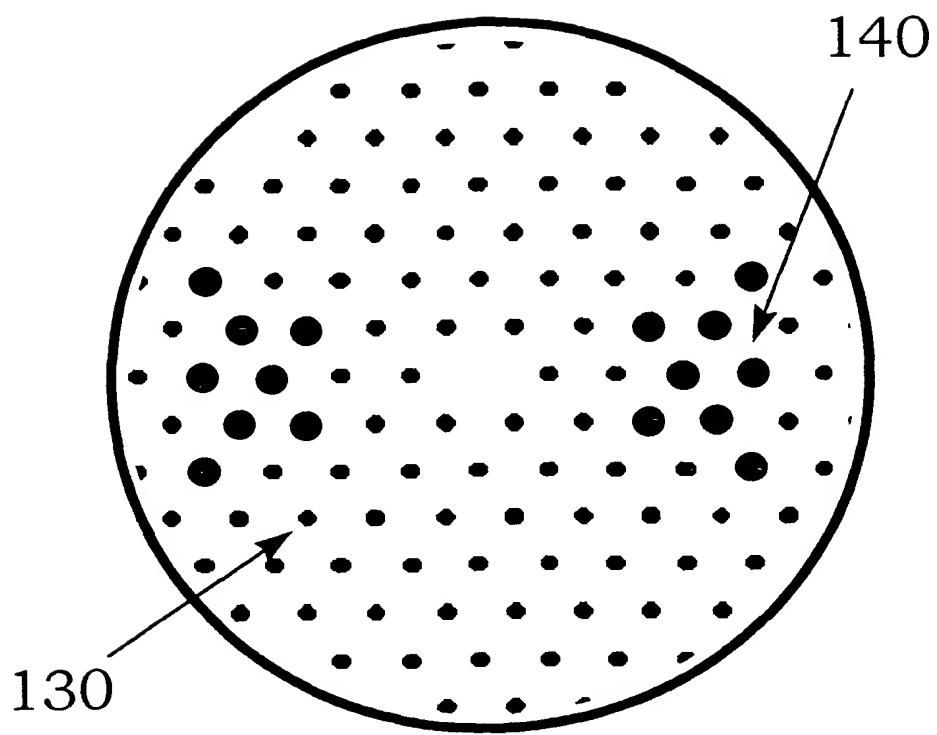
Fig. 6





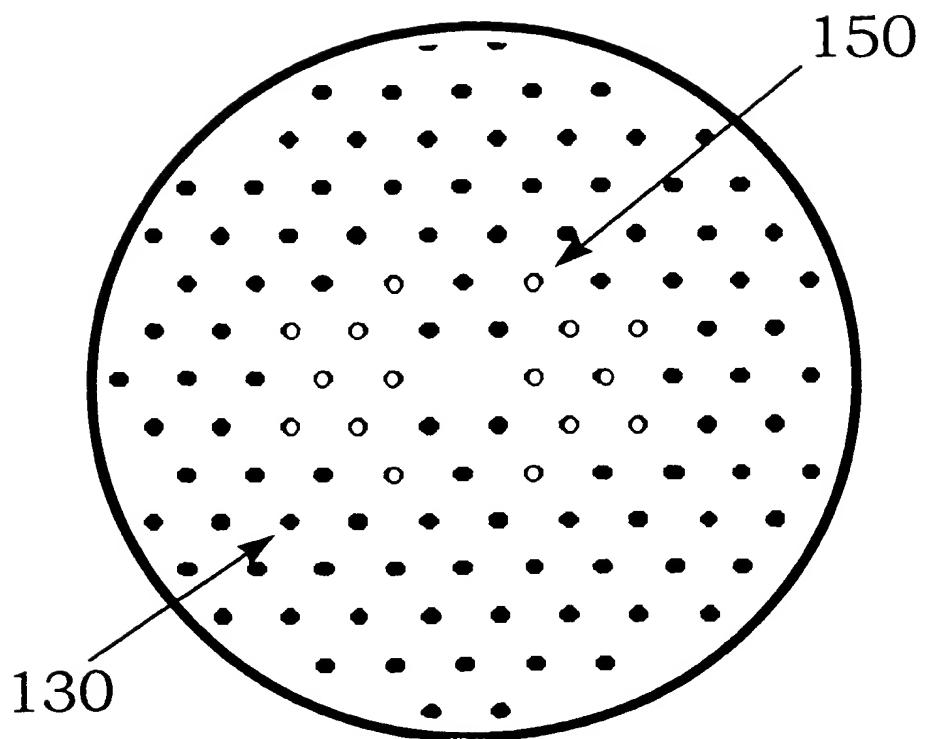
7/10

Fig. 7



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Fig. 8





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Fig. 9

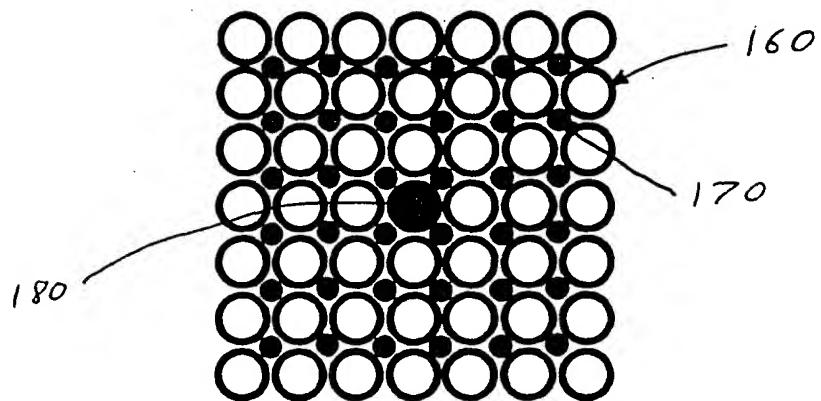
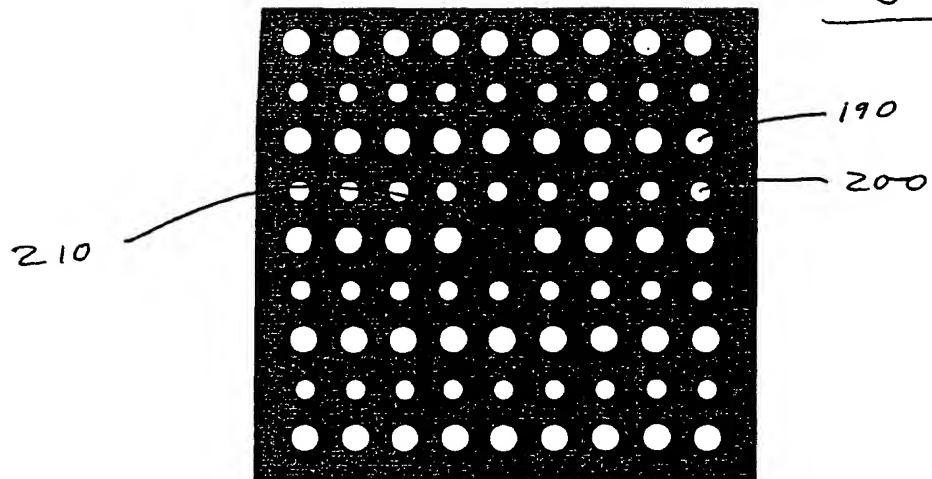
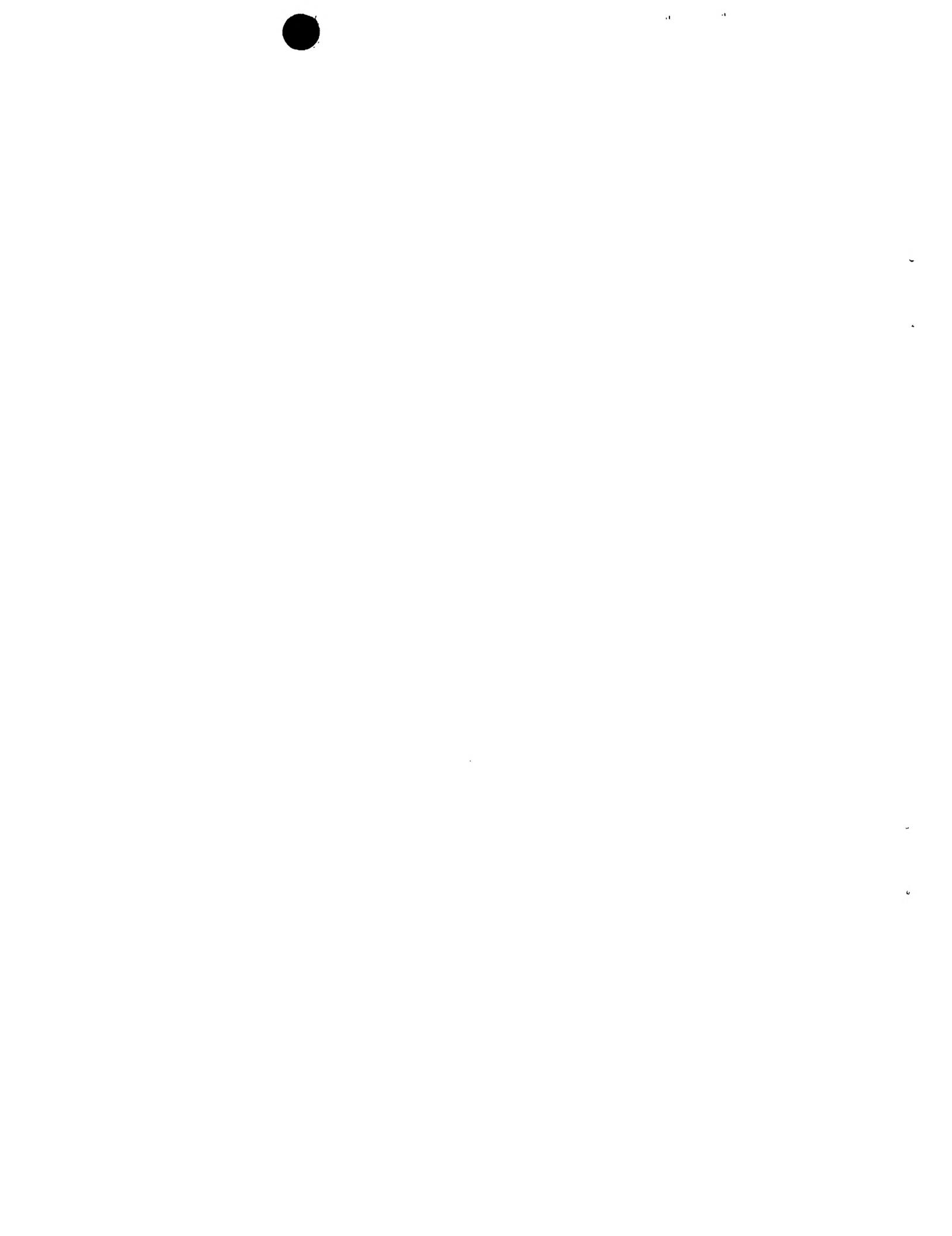


Fig. 10





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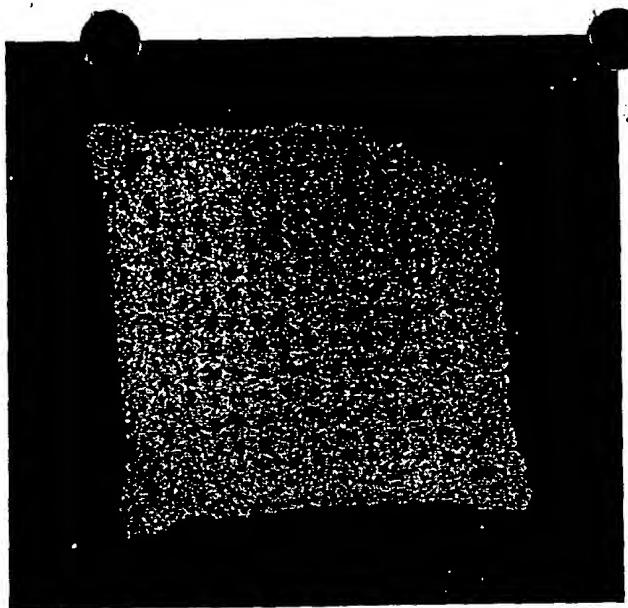


Fig. 11

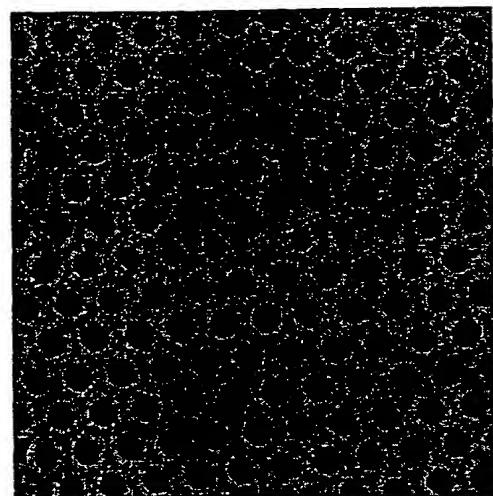


Fig. 12

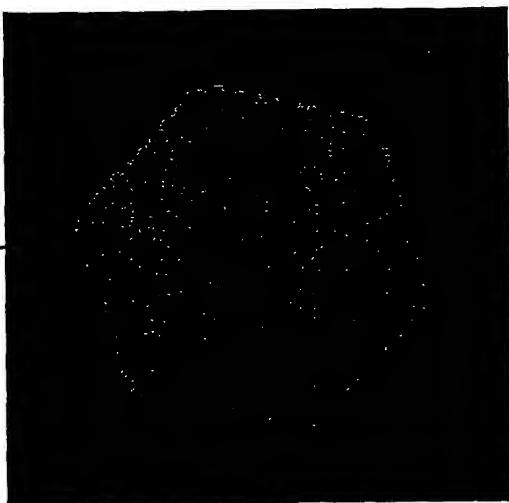


Fig. 13

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